Kinetic understanding of Neoclassical Lithium Transport

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and **the CPES Team**

PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

CPES
Center for Plasma Edge Simulation

Outline

- **Introduction**
  - High level introduction to neoclassical impurity transport
  - Introduction to XGC0 kinetic transport code
- **What is seen in the H-mode experiment?**
  - Drop of carbon density at L-H transition: probably a transient (ion-scale) turbulence/neoclassical phenomenon (future topic for the XGC1 edge gyrokinetic turbulence code)
  - **Li appears to come in only in the early stage, following L-H transition**
  - **Then, the Li penetration through the pedestal and into the core are blocked.**
  - **Reduction of C and Li in a thin layer toward separatrix**
  - **Reduction of $P_{L\text{-}H}$ with Li, with Broadening of n_e pedestal**
  - And others
- **Relevance of Neoclassical Physics to Edge: validation**
- **What does XGC0 say?**
- **Discussion and conclusion**

Executive description of neoclassical impurity transport theory

$$\Gamma_\alpha = -\Sigma_\beta \left[A_{\alpha\beta} \; \langle \partial \mathit{ln}\ p_\alpha / \partial r - (Z_\alpha / Z_\beta)\ \partial \mathit{ln}\ p_\beta / \partial r \rangle + B_{\alpha\beta}\ \partial \mathit{ln}\ T / \partial r\right]$$

Diffusive, normally from random pitch angle scattering

- ❖ If the main ion species α is in banana regime, $B_{\alpha\beta}$ can be <0 → “temperature gradient screening” of impurity influx
- ❖ **How do we make a guess of the radial impurity transport direction?**
  - **Lighter ion species see the heavier species more as a pitch angle scattering background → normal random walk diffusion→ diffuses downward in pressure gradient → radially outward transport**
  - **Heavier ion species see the lighter species more as a friction source → momentum conservation in the collision with lighter species dominate the transport direction → radially inward transport**
    - M_C (12, Z=6) >M_{Li} (6, Z=3)>M_D
    - M_{Ne} (20, Z=10) >M_C (20, Z=6) >M_D

XGC0: Kinetic transport modeling code

- **Full-f Particle-in-cell in 3D perturbed magnetic field (RMP, ripple)**
- **Realistic geometry from geqdsk data (wall and separatrix included)**
- **3D (in r-space) + 2D (in v-space) ion and electron Lagrangian dynamics with self-consistent 1D E_r evolution**
- **Electrostatic potential Φ is assumed to be a flux function**
- **Logical sheath at diverter plates ($J_\perp + J_{||} = 0$ out of a flux tube)**
- **D/H Neutral Monte Carlo particles with a wall recycling coefficient**
- **Conserving Monte-Carlo Coulomb and neutral collisions (ionization and charge exchange)**
- **DEGAS2 is coupled-in (Stotler)**
- **Multiple ion species with Hirshman collision operator**
- **Heat and momentum fluxes from core**
- **Implementation of anomalous transport modeling: random walk and convection. Independent control of the ambipolar particle and the heat transport on each species**
- **XGC-RF contains rf operator**
- **More self-consistent anomalous transport is to be imported from XGC1.**

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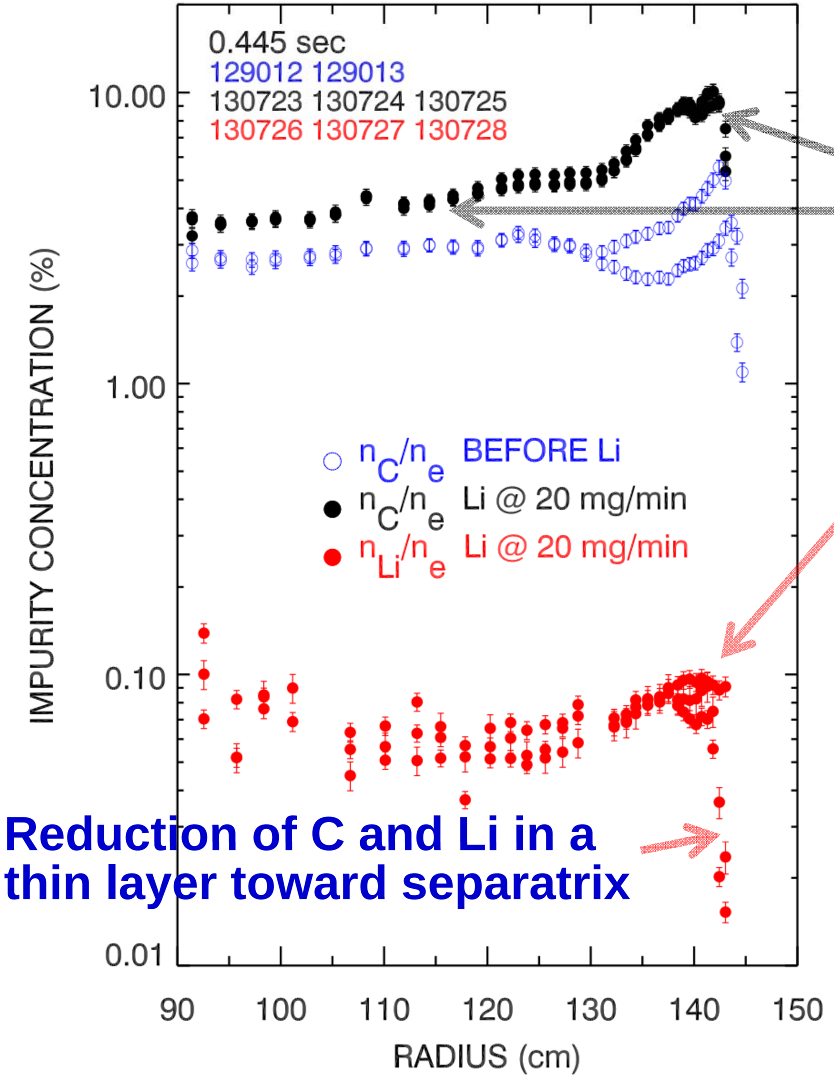
New Lithium Density Measurements in H-mode

(We will try to connect the blue items with XGC0 simulation results.)



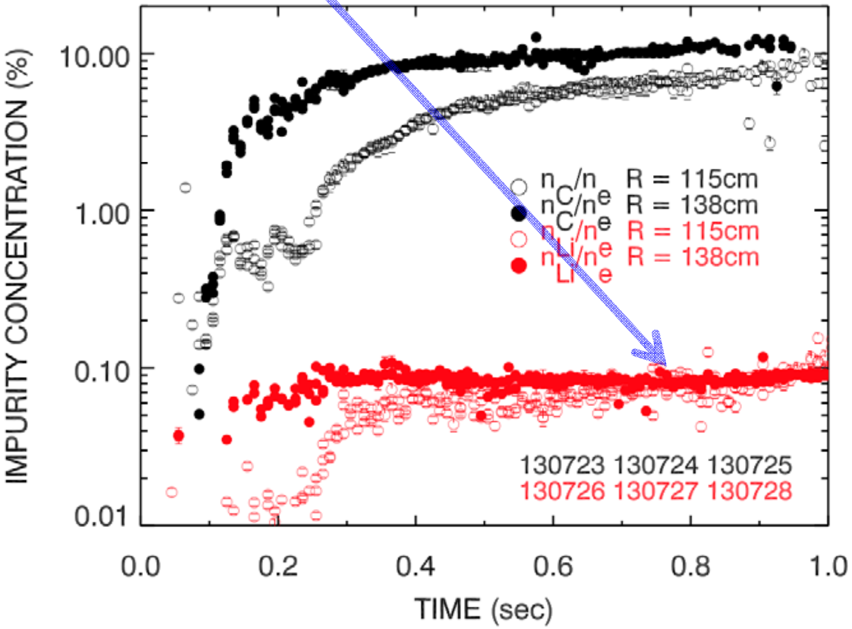
Reduction of C and Li in a thin layer toward separatrix

Figures are from R. E. Bell.

- Large drop of n_C at L-H transition into hollow profile → Probably a transient, nonlocal turbulence effect
- **Carbon increases with Li evaporation**
  - **C influx rate across pedestal is high**
  - **C accumulation in core**
- **Li screening at later time, but not earlier**
- **P_{LH} goes down with Li**

Li influx rate across the pedestal is low

“No sign of Li accumulation in core”



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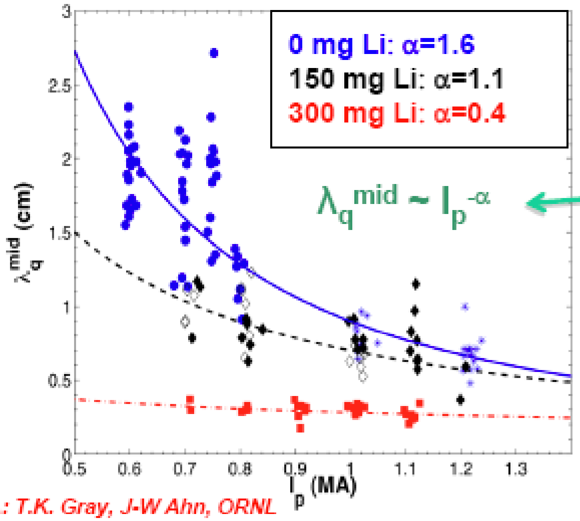
Is neoclassical physics relevant to edge physics: validation?

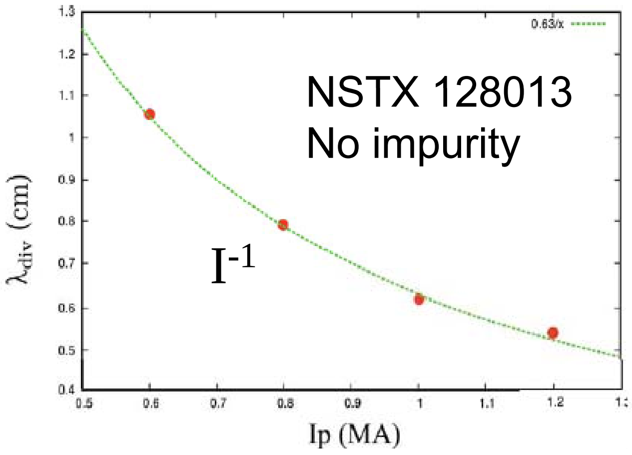


IAEA: T.K. Gray, J-W Ahn, ORNL

**Joint Research Target (3 U.S. Facilities)*

- Divertor heat flux width decreases with increased plasma current I_P
  - Potentially major implications for ITER
  - NSTX: λ_q^{mid} further decreases with Li

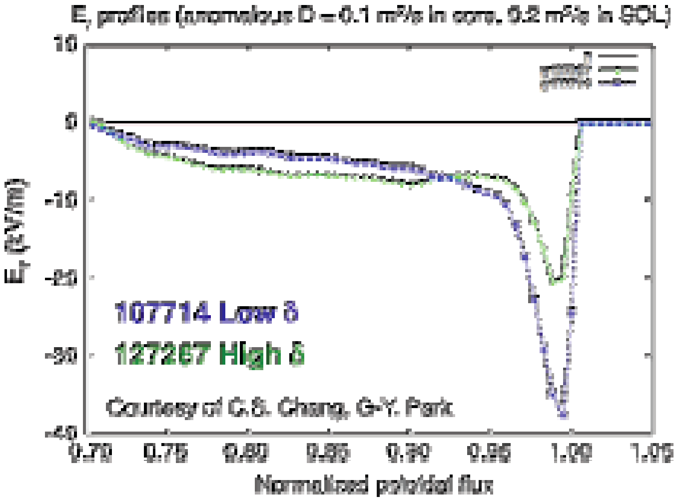
→ NSTX Upgrade with conventional divertor (LSN, flux expansion of 10-15) projects to very high peak heat flux up to 30-45MW/m^2



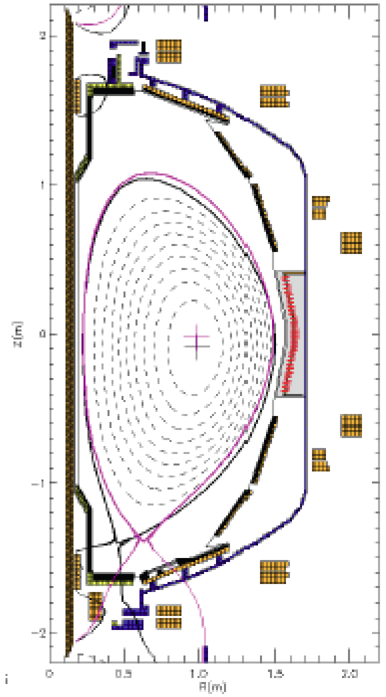
Neoclassical orbit broadening/squeezing physics:
XGC0 shows $\lambda_q^{mid} \propto I_P^{-\alpha}$, where α is function of collisionality, with some broadening by radial anomalous transport.

Predictive validation of neoclassical physics from XGC0

R_X depoendence of ExB shearing rate, thus possibly affecting P_{LH}, was predicted from XGC0 several years ago.

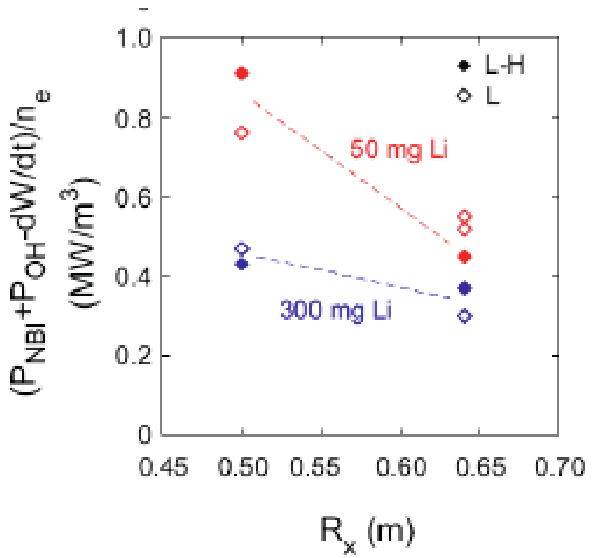


Courtesy of C.S. Chang, G-Y. Park

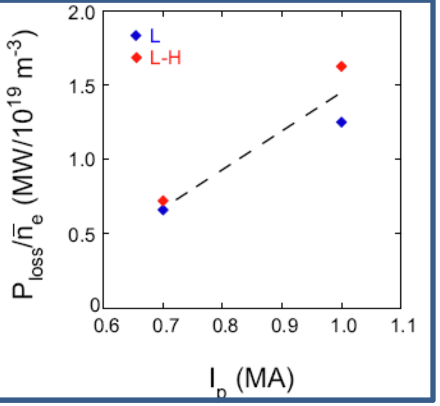


Then, validated in NSTX recently. With and without Li

D.J. Battaglia, C.S. Chang, S. Kaye, R. Maingi, et al, TTF2011



Other neoclassical physics, such as I_p dependence of ExB shearing rate, thus of P_{LH} (Kaye, et al, IAEA2010) was also predicted by XGC0, and validated.



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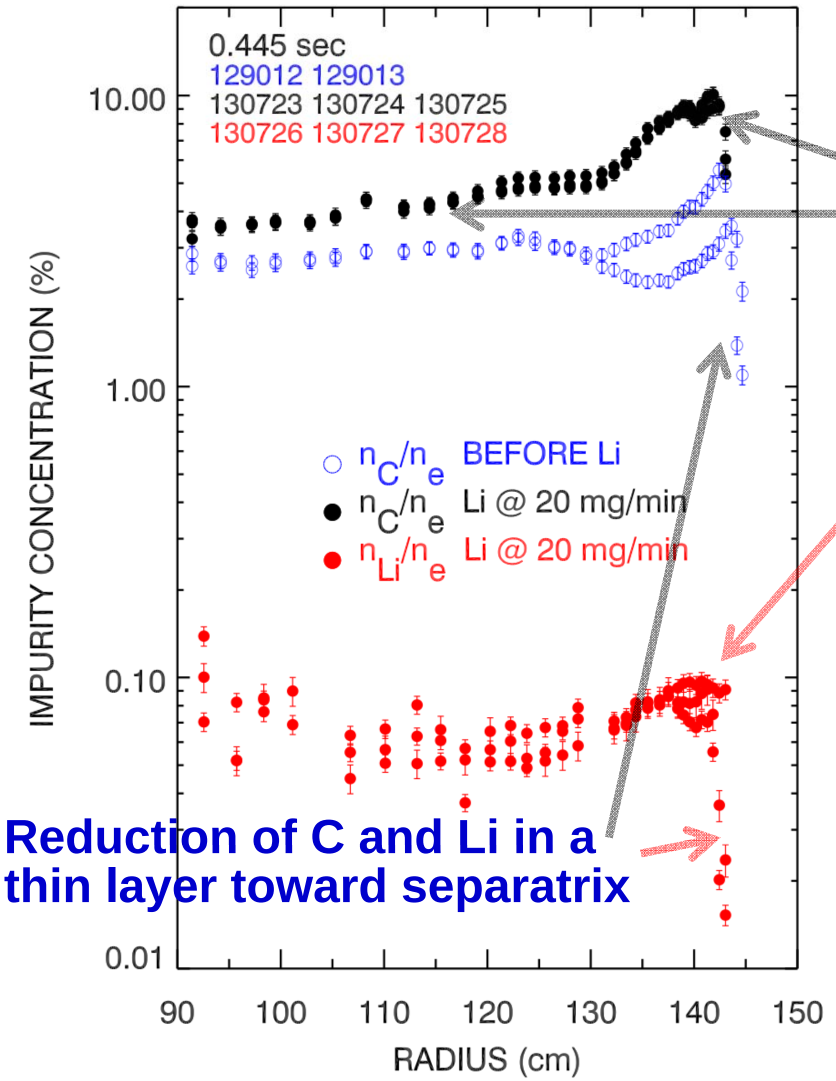
Kinetic neoclassical impurity transport simulation

- **Anomalous transport is off → Purely Neoclassical**
- **Simulation domain: ψ_N=0.4 to wall in realistic g_eqdsk magnetic field geometry (g124439.00497)**
- **5 species: D^{+1}, e^- , D^0, C^{+6}, Li^{+3} or Ne^{+10}**
- **Recycling rate for C^{+6} and Li^{+3} or Ne^{+10} are independently controlled relative to D^+ (simplified model)**
- **Large initial C^{+6} density (10% uniform in space) and small Li or Ne density (1/2 or 1/33 of n_C, uniform): basic “physics” study, not a discharge “simulation”**
- **Initial temperatures are assumed to be equal between species.**
- **Self-consistent E_r and $V_{||}$ with the impurity and edge effects (wall, X-point, neutral, pedestal, etc)**
- **Radial transport speeds are calculated while the initial profiles are being evolved consistently with E_r and $V_{||}$.**

New Lithium Density Measurements in H-mode



- **Carbon increases with Li evaporation**
  - **C influx rate across pedestal is high**
  - **C accumulation in core**
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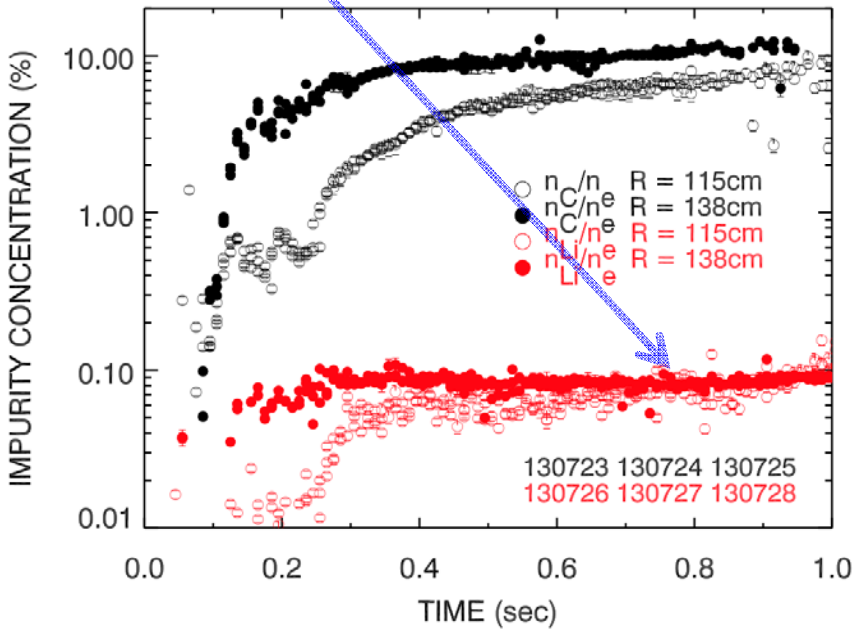
Li influx rate across the pedestal is low

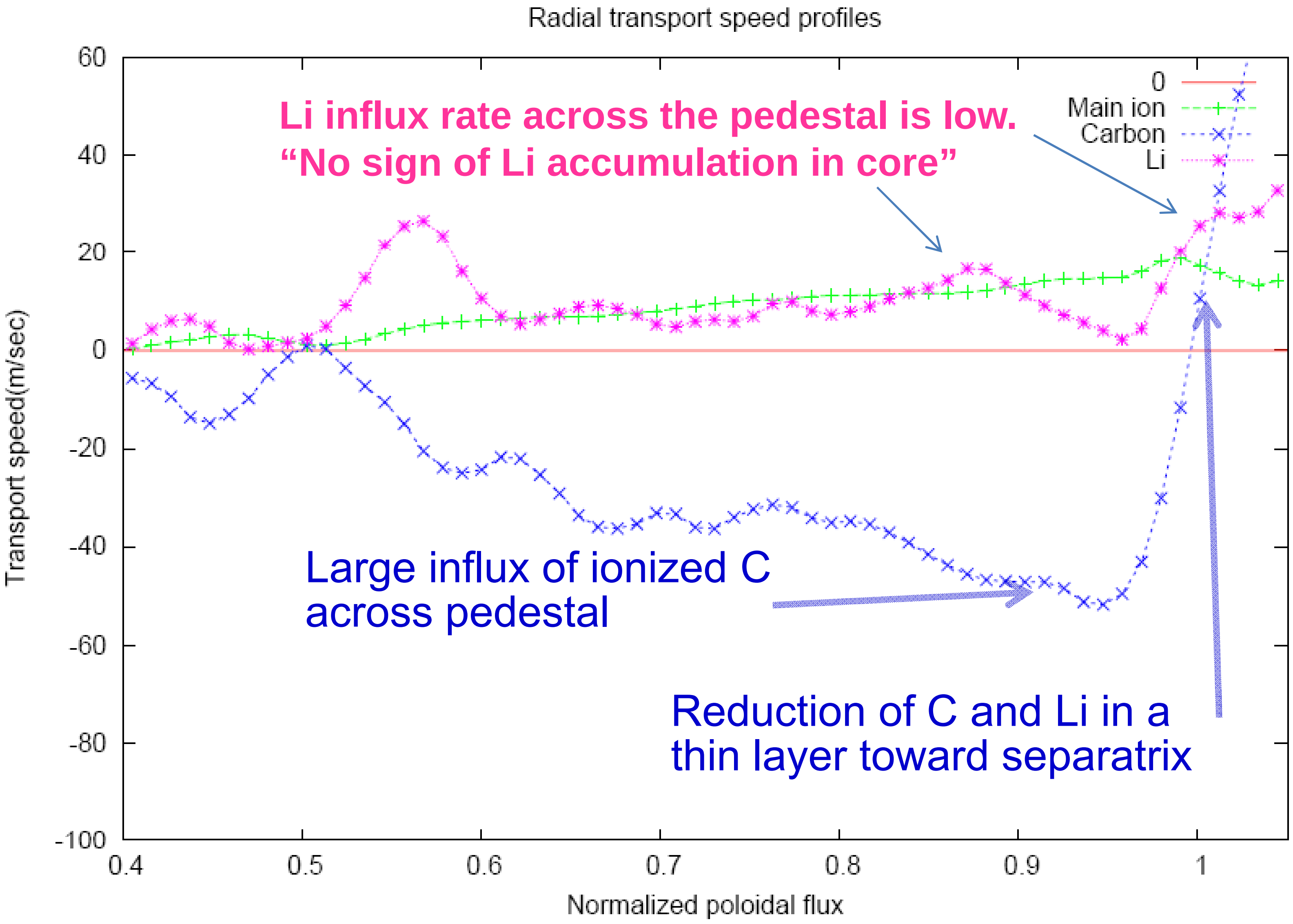
"No sign of Li accumulation in core"

Reduction of C and Li in a thin layer toward separatrix



Figures are from R. E. Bell.

XGC0 says, at $n_C/n_e=10\%$, Li moves outward while C^{+6} moves in at $\psi_N<1$.



Li influx rate across the pedestal is low.
“No sign of Li accumulation in core”

Large influx of ionized C across pedestal

Reduction of C and Li in a thin layer toward separatrix

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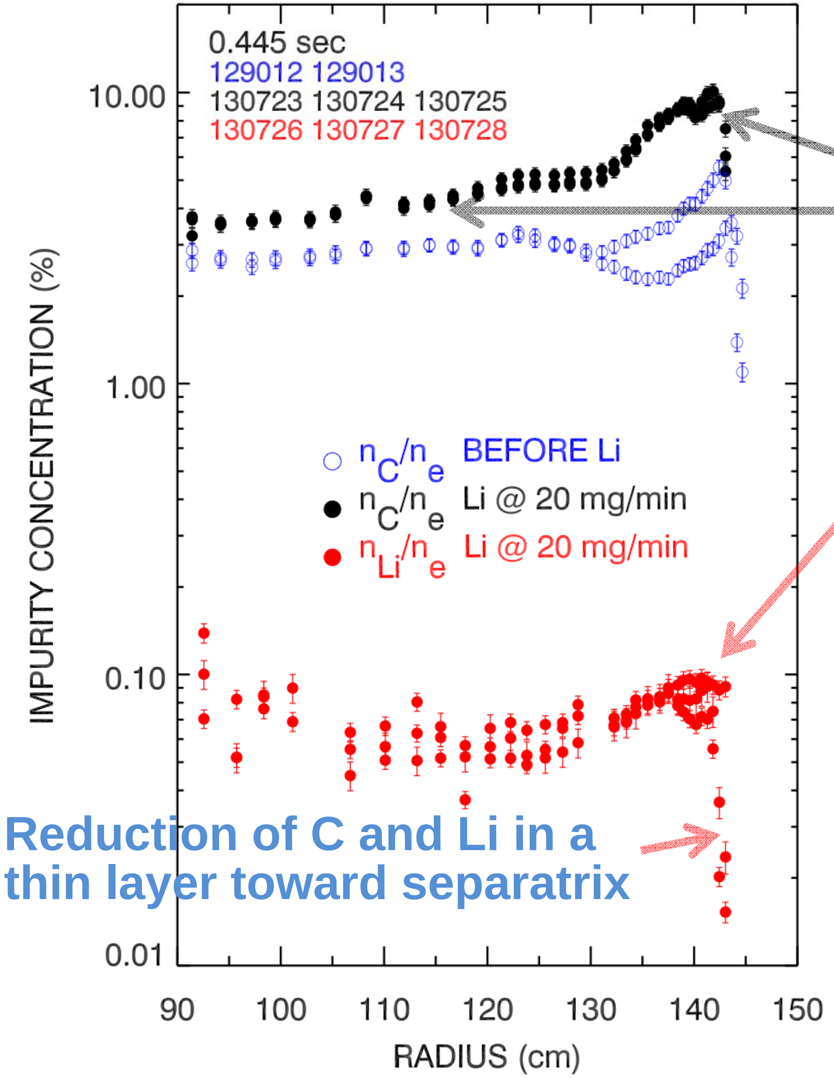

- Carbon increases with Li evaporation
  - – C influx rate across pedestal is high
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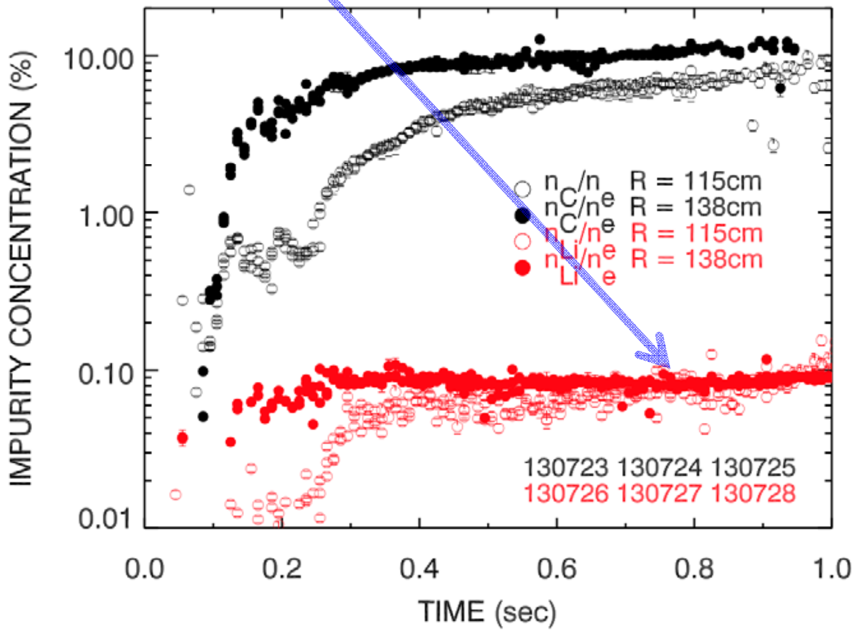

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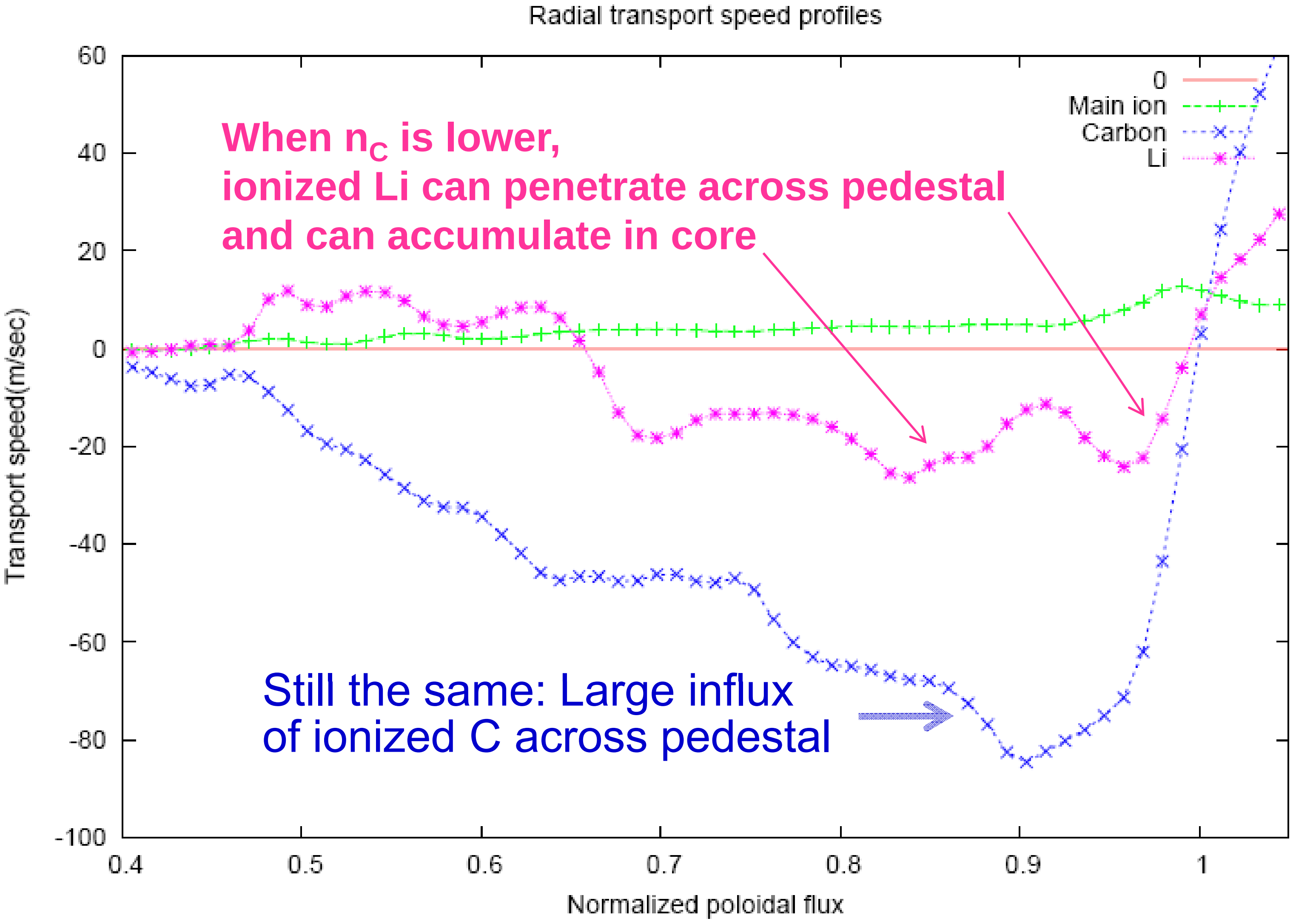
Figures are from R. E. Bell.

At 5% n_C/n_e, Li moves inward at much slower speed than C.



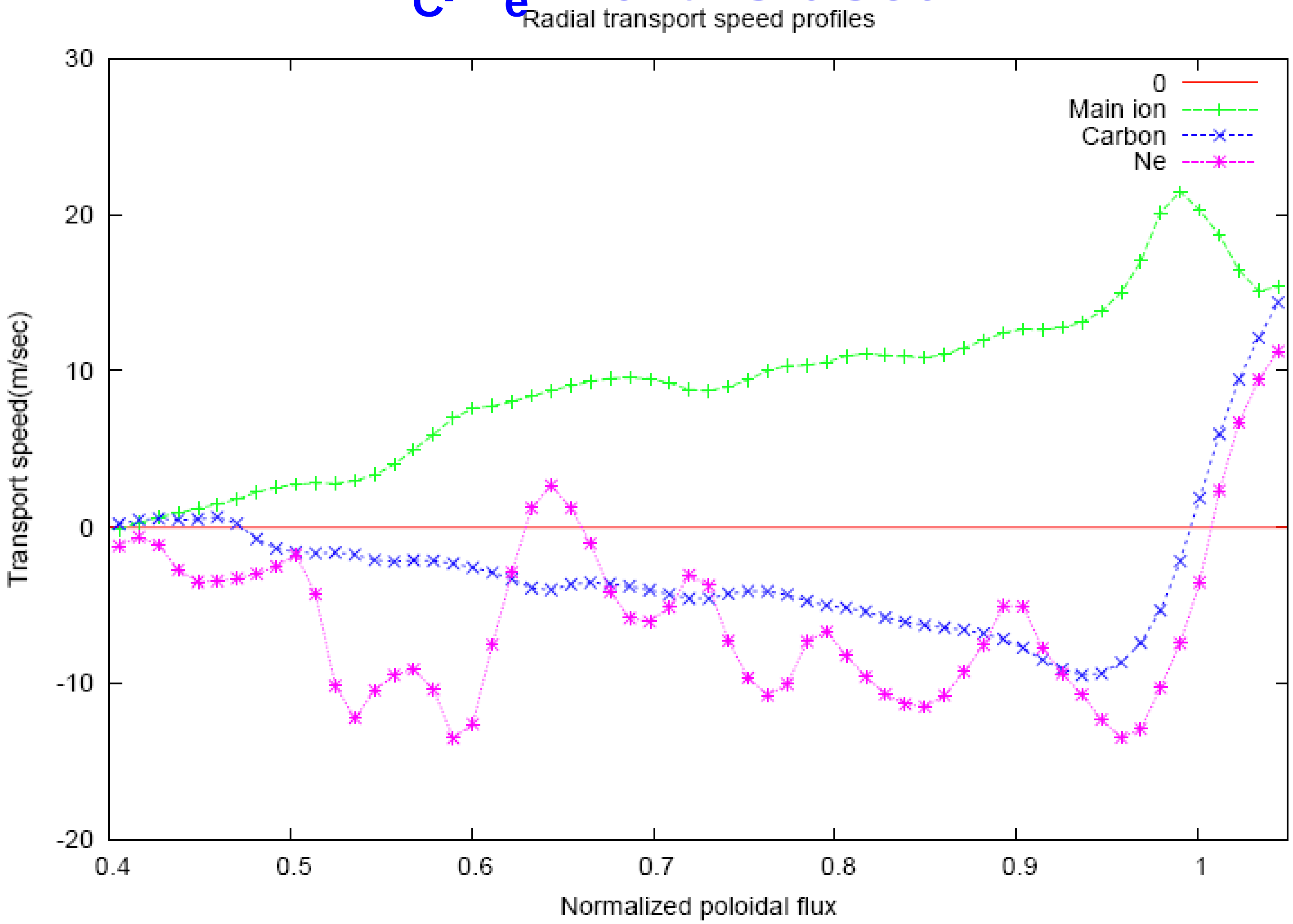
When n_C is lower, ionized Li can penetrate across pedestal and can accumulate in core

Still the same: Large influx of ionized C across pedestal

Validation with Ne

- Ne has opposite property to Li against C.
- Will Ne show opposite behavior to Li in the same situation?
- Will C show different behavior by Ne?
- Expectation from neoclassical physics:
  - Inward transport speed of C will be reduced.
    - C will collide against D → inward flux
    - C will scatter against Ne → outward flux
  - Ne will collide against D and C and move inward

XGC0 says Neon ions move inward together with the carbons, but C influx is at slower speed than the Lithium case; n_C/n_e=10% is used.



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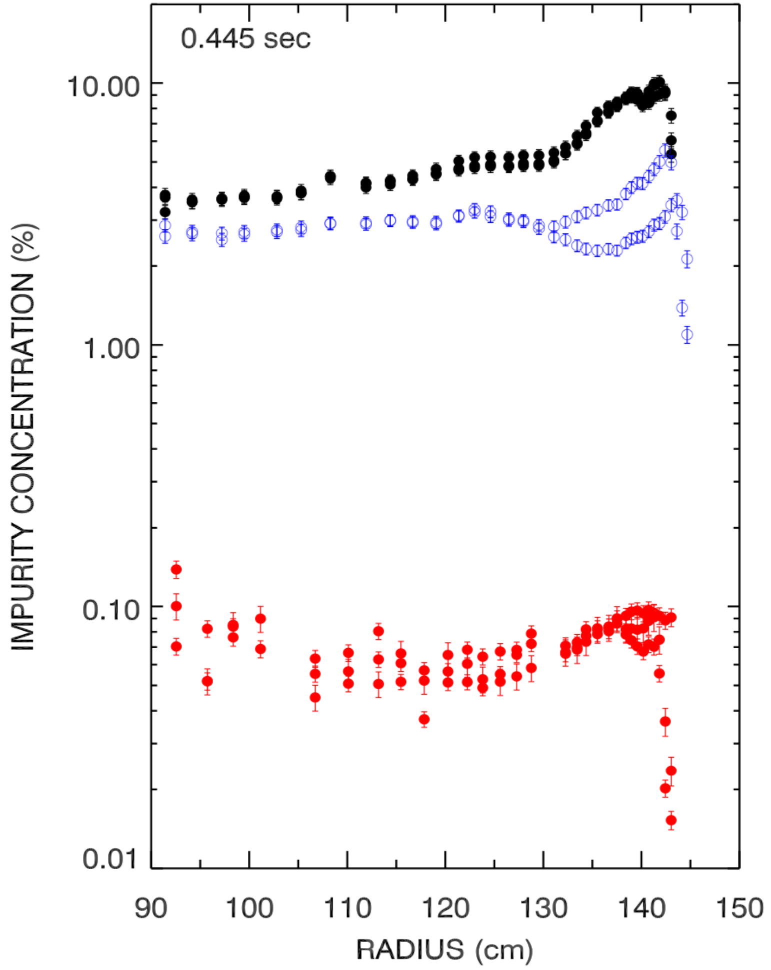
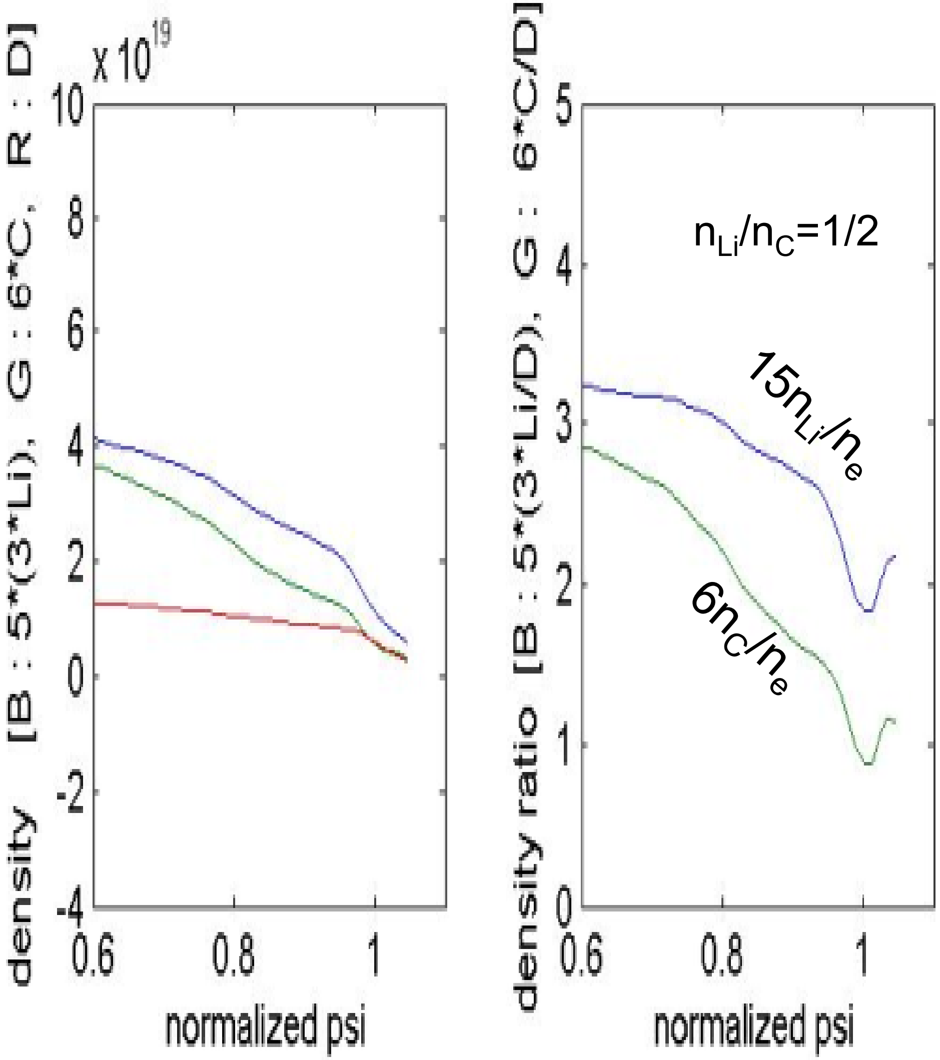
n_C/n_e and n_{Li}/n_e show “dip” in the pedestal.

NSTX experiment

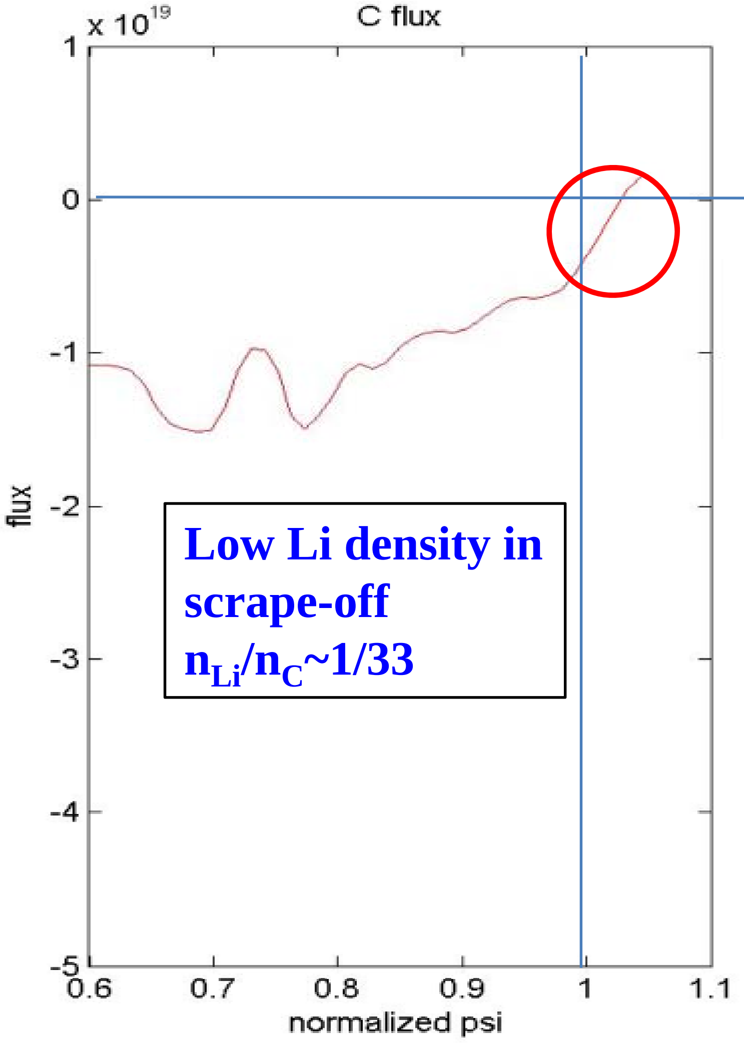


Large Li density case

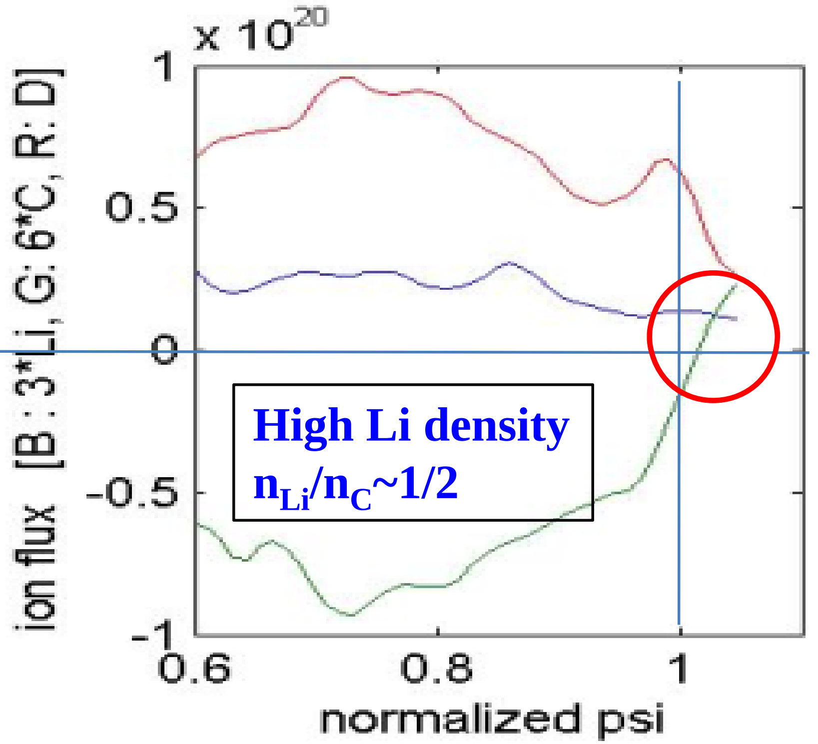


More realistic impurity profile simulation is needed for quantitative comparison.

The n_C dip is caused by Carbon screening in the scrape-off layer



Low Li density in scrape-off
n_{Li}/n_C~1/33



High Li density
n_{Li}/n_C~1/2

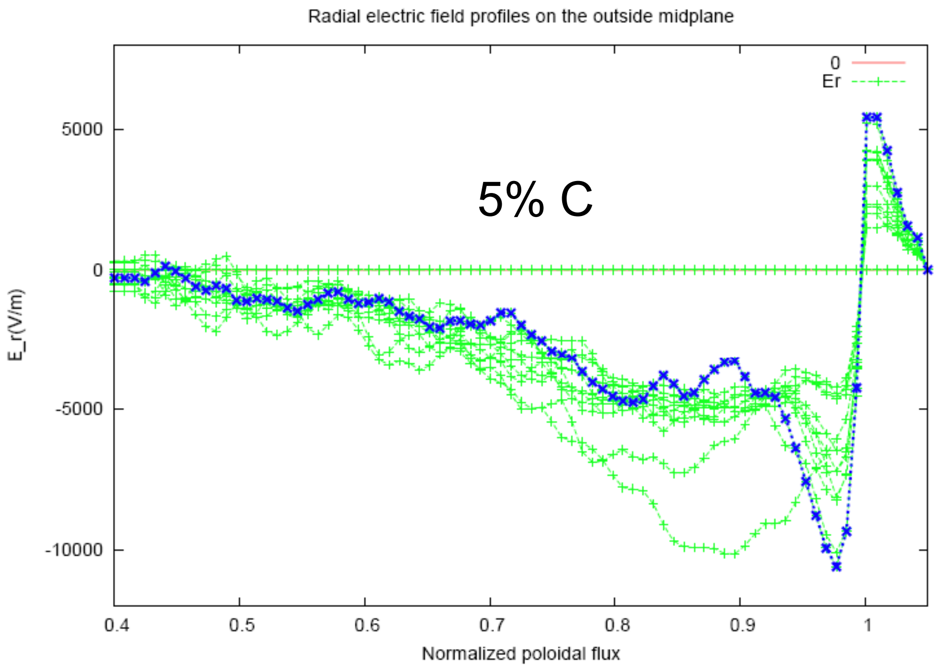
At high n_{Li}, carbon ion infux from the scrape-off layer is blocked (C^0 can still penetrate)
→Lower carbon density in pedestal
→Higher ExB shearing rate
→Lower P_{LH}

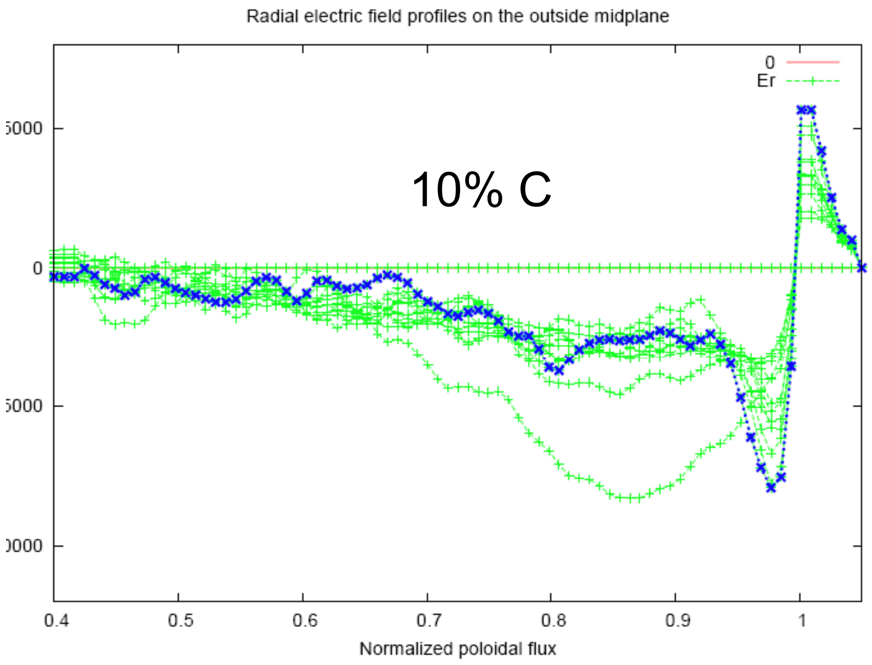
Carbon depletion strengthens ExB shearing

E_r-well depth/width at n_C/n_e=5% is stronger than at 10%

Weaker X-loss effect by C in pedestal

$V_{\nabla B}\propto 1/Z$, $v_{||}\propto 1/m^{1/2}$: Thus, $V_{\nabla B}/v_{||}\propto m^{1/2}/Z$: where $Z_C/Z_D=6$, $(m_C/m_d)^{1/2}=$**$6^{1/2}$**


Radial electric field profiles on the outside midplane


Radial electric field profiles on the outside midplane

Conjecture: Reduction of $P_{L\text{-}H}$ with abundance of Li in the scrape-off layer:

- Reduction in C^{+6} in the pedestal by high Li population in the scrape-off layer
- Momentum conservation is not a constraint in scrape-off: Collisional transport yields $\Gamma_C>0$ just outside separatrix. → higher C collisionality by abundant Li, → higher $\Gamma_C>0$ just outside separatrix → more C depletion in pedestal → Increased ExB shearing rate.in pedestal

Conclusion and Discussion

- **It appears that many of the Li behaviors and its influence on plasma in the H-mode, as seen in NSTX, could be related to neoclassical physics**
  - Blockage of Li influx, except in the early low-carbon stage, following the L-H transition
  - Enhanced flux of ionized C into core throughout H-discharge period
  - Reduction of C and Li in a thin layer toward separatrix
  - Lower $P_{L\text{-}H}$ with Li evaporation
  - Broadening n_e pedestal
- The initial large drop of C into hollow profile appears to be outside of neoclassical physics: A transient turbulence-neoclassical effect is suspected

  → to be investigated from XGC1 gyrokinetic edge turbulence-neoclassical code
- **A more realistic plasma "simulation," as opposed to the "academic" study, is needed and in progress (part of PhD thesis, K.H. Kim)**
- **Divertor heat load scaling with Li is to be studied. ADAS data to be used, in collaboration with the Auburn group.**